REVIEW

Digital radiography. A comparison with modern conventional imaging

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The development of computed radiography over the past two decades has transformed radiological imaging. The radiology departments in the 21st century will look very different from those in the preceding period. In this review, the development of digital radiography is presented with a description of its various forms and a comparison with screen film radiography.

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Wilhelm Roentgen, professor of experimental physics in Germany, discovered *x* rays in 1895 while working on emissions from electric current in vacuum. He noticed a glow from a barium platinocyanide coated screen kept across the room whenever the current was passed between the two electrodes in a charged cathode tube. A few weeks of intense experimentation led to a report to the local medical society in Germany and deservedly, the first Nobel Prize in Physics in 1901. Over the years, many significant refinements were made in the techniques and the equipment. Presently, radiological facilities are found in even the smallest hospital and emergency units involved in health care. A hospital without radiography is inconceivable.

Fluoroscopy was introduced shortly after Roentgen's discovery of *x* rays. The most significant use of fluoroscopy is intraoperative use as in image intensification during orthopaedic, vascular, urological procedures. It is also used for dynamic radiographic investigations.

The next important change came about with the development and widespread use of computer technology. Application of computers to radiography was inevitable. The idea of a filmless radiology department was fascinating to medical professionals. Digital radiography was introduced in the mid-1980s[1] and, with a steady gain in popularity, it is now competing with conventional screen film radiography (SFR) in all radiographic applications.

CLINICAL APPLICATIONS AND DIAGNOSTIC ROLE

Radiographs are the starting point for diagnosis of a variety of clinical situations; the clear advantages being their easy availability, low cost, non-invasive, familiarity to medical professionals, relative harmlessness, and fast imaging times. Combine this with excellent resolution and contrast; it is not difficult to understand the key role of radiographs in the medical sift.

Conventional radiography (also known as SFR) is still used more widely than digital radiography but this dominance is fast dwindling. The reasons behind the declining popularity of SFR are—fixed dose latitude, fixed non-linear grey scale response, and limited potential for reducing dose to the patient. All these parameters limit the information that can be captured on film. The images cannot be changed in contrast once they have been processed. Apart from this, film is expensive, uses hazardous materials for processing, is labour intensive, and long term storage and retrieval of film is difficult. SFR is not compatible with the picture archiving and communication systems (PACS).

Digital radiography (DR) has further evolved into different forms. In computed radiography (CR), a photostimulable phosphor plate is used for detection of *x* rays instead of the conventional film screen. The exposed plate is scanned with helium neon laser and the emitted light is captured by photomultiplier tube and converted to analogue electrical system, which is then digitised. Another form of DR is direct radiography in which a semiconductor based sensor directly converts *x* ray energy into electrical signals, hence eliminating the middle step of latent image and image plate reader. Solid state detectors (selenium drum) and flat panel detectors (selenium and cesium iodide) are used as scintillators, which convert *x* ray photon to light and this is converted to electrons via amorphous silica arranged as photoiodide transistor. Image intensification, which is used for real time images, uses digital sensor linked to video monitors and this is extremely useful for screening during radiological, vascular, and orthopaedic procedures. It increases the brightness by up to 6000 times without increasing the radiation dose.

RADIOGRAPHIC IMAGING EQUIPMENT

x Rays are produced by bombarding a metal target by high energy electrons. In conventional radiography, *x* rays passed through the human body are absorbed, which causes attenuation of the incident beam. The uniform *x* ray beam emitted from the source is modulated as it passes through the human body and these changes are recorded on the film.

The contrast in an *x* ray image depends on differential attenuation of *x* rays as they pass through different body tissues. In the absence of

Abbreviations: SFR, screen film radiography; PACS, picture archiving and communications system; DR, digital radiography; CR, computed radiography contrast media, the *x* ray contrast depends on Crompton effect for soft tissue and a combination of the Crompton effect and photoelectric effect for bone. Contrast can be further improved in some areas by giving contrast media. The photoelectric effect predominates for iodinated contrast media because of its K edge at 33 KeV and Barium 37 KeV. Plain radiographs have one of the best spatial resolutions (0.1 mm) of all the imaging modalities. The beam is received on a silver bromide plate sensitive to the electromagnetic radiation and it leads to production of black metallic silver from silver bromide. A comparatively small dose of *x* rays is used to produce a subtle change in the plate, which is then amplified by chemical development to become visually identifiable.

The *x* ray equipment must be calibrated to accurately produce the desired voltage, current, and exposure time. This has to be frequently checked to ensure correct radiation dose. The film is composed of supercoat—protective layer of hardened gelatin; emulsion—radiosensitive silver halide grains suspended in gelatin; adhesive layer and film base. The amount of silver bromide is directly proportional to the sensitivity of the film.

In SFR, the film acts as the medium for acquisition, display, and storage of images. On the other hand, the production of image in CR can be considered over four discrete broad heading—image acquisition, processing, storage, and display. All these four processes are separate and the performance of each can be optimised individually for maximum efficiency.[2] Phosphor plates containing a thin layer of fine grain crystals of Barium fluoro halide doped divalent Europium (Eu^+) are used in CR instead of silver halide plates used in conventional radiography.[3] Incident *x* ray photons are absorbed by the phosphor crystals producing high energy photo electrons. The electrons are trapped at Halide vacancies (colour centres) to form F centres. A helium neon 633 nm laser beam is used to scan the plate. The colour centres absorb energy and electrons drop to low energy level with release of energy in the form of light photons. These photons are converted to electric current by high sensitivity photo multiplier tube. The analogue electrical signal is then digitised to provide the image and this can either be printed from a laser printer or viewed on grey scale high resolution monitors. Images can be stored on PACS and easily retrieved at a later date if required. Images can be accessed from any terminal and by multiple users.

SPECIAL TECHNICAL FACILITIES AND PHYSICAL PRINCIPLES

In digital imaging, the detector should ideally detect even small amounts of incoming quanta and have a high dynamic range so as to detect subtle findings without adding artefacts. Detector efficiency is the percentage of photons emanating from the subject that lead to formation of image. Phosphor plates are two to four times faster than film screens. A higher efficiency implies a lesser dose of *x* rays in required. Signal normalisation helps to get an optimal image and the quality of image can be changed even after the exposure has been made with a certain radiation dose.

The image quality in a digital system depends on the quality of *x* ray equipment, applied dose, and additionally on pixel size, pixel depth, signal to noise ratio, and dynamic range. The Shannon Theorem states that if the pixel size is smaller than the smallest detail that has to be visualised, then there will not be any loss of information. A variety of measures exist to assess the image quality and these include pixel size, intensity transfer function, modulation transfer function, noise equivalent quanta, and detective quantum efficiency.

The intensity transfer function (characteristic curve) depicts the relation between the dose at detector entrance to intensity of resultant image. The dynamic range of the image plate is the ratio of maximum and minimum doses that can be imaged. For film screen images, the curve is S shaped with a short dynamic range of 1:40. Digital detectors have a linear curve that permits further processing and the dynamic range is between 1:100 to 1:1000 or even more (fig 1). This is important in areas of body with high contrast—as between bone and soft tissues or in areas where there is an acute change in body thickness—as in the region of neck. In such situations, the use of phosphor plates allows for a sharp image and lesser number of repeat examinations as the detector is able to adjust to the different dose of incident radiation coming through body parts of varying thickness.[3]

The image plates can be either standard (ST-V) with a 230μ thick phosphor plate or high resolution (HR-V), which are higher resolution plates used in musculoskeletal radiography. The HR plates require two to three times higher radiation dose compared with ST-V but are useful in musculoskeletal radiography because of its better image quality.

RADIOGRAPHIC AND OPERATIONAL ASPECTS OF THE IMAGING SYSTEM

The keystones on which the SFR survives in current radiological practice are resolution and familiarity of the medical profession. The high resolution makes it useful to diagnose undisplaced fractures and in other situations like subperiosteal erosions in hyperparathyroidism.

One of the many advantages of CR is that all the constituent processes—image acquisition, processing, display, and archiving—are individual and separate. This in turn leads to secondary advantages like, for example, a reusable image plates, a linear response over a wide dynamic range, ability to process an image after acquisition, and sharing the images over a network electronically. It also makes storage of a large amount of images in a comparatively much smaller space and quick access for later reference. Conventional film is subject to loss through storage and the images may deteriorate with time, and this problem does not exist for digital images. The processing enables the technologist to change the image optical density after image capture and hence avoiding another exposure to the patient.

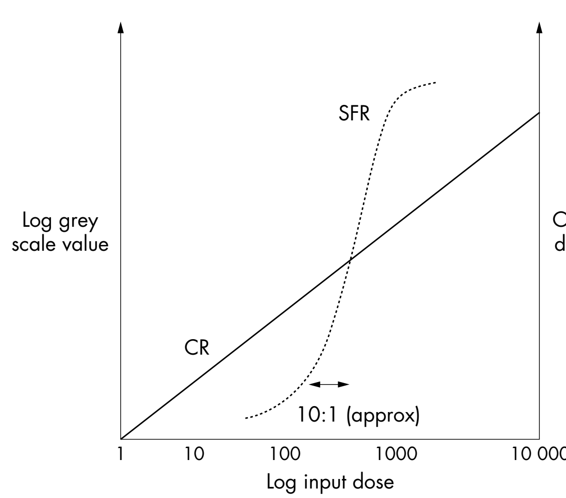

Figure 1 Detector response of conventional radiography has a short linear segment while the digital radiographic plates have a long linear relation.

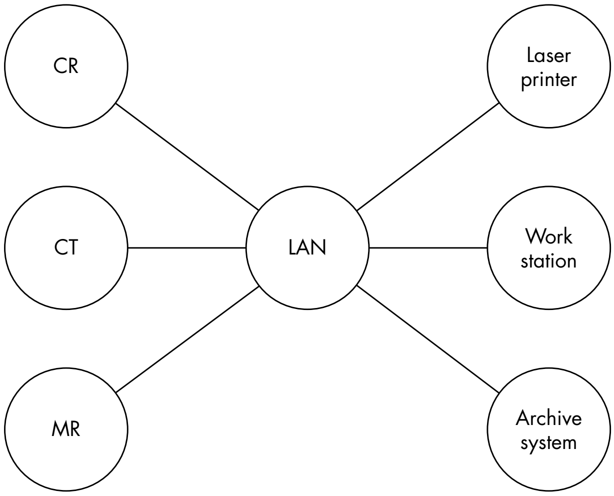

Figure 2 An example of a local area network connected to the digital imaging modalities and providing output on a work station and a laser printer. It is connected to the archive for storage and access. CR, computed radiography, CT, computed tomography; MRI, magnetic resonance imaging.

IMAGING SYSTEM DESIGN TO ACHIEVE THE OPTIMUM IMAGE

The ideal imaging system should permit a high quality image with minimal radiation exposure. DR has the potential to achieve this and further advances will possibly lead to lowering the radiation dose and using higher sensitivity plates to give good resolution and sharpness of images.

Portable radiography is another significant reason to adopt DR. It is useful in patients with multiple trauma for imaging the neck, pelvis, and chest as part of the ATLS protocol. The long linear response permits adjustment for attenuation and maintains the image quality.

LIMITATIONS IN CURRENT IMAGING SYSTEMS

Limitations of the SFR system are related to storage, cost, and film distribution. Also, the dose to the patient cannot be reduced and screen film has fixed non-linear grey scale response and fixed dose latitude.

The shortcomings in CR images were believed to be limited spatial resolution, which is typically 2.5 to 5 lines per mm (lpm) while the SFR provides 2.5 to 15 lpm resolution. There have been a multitude of studies investigating the spatial resolution of SFR compared with CR. One such comparative study on imaging of hand showed the resolution of CR to be at least as good as SFR.[4] Another study of interpretation of 122 musculoskeletal radiographs by four readers showed a resolution of 2048 × 1680 × 12 bits to be sufficient to detect subtle findings and this corresponds to 2.5 lines per mm.[5] At this resolution there was no difference in diagnostic yield between digital and conventional radiographs. Magnification techniques in CR may overcome the constraints imposed by limited spatial resolution in CR.[6] The edge enhancement filter in DR enhances subtle findings on chest radiographs. Piraino compared selenium based DR with conventional SFR (100 speed) for hands and feet in 24 patients and the films were evaluated by five experienced radiologists.[7] Selenium based radiography was found to be equivalent to conventional radiography in showing bones, soft tissue, and trabecular detail by all observers.

A resolution of over 2.88 line pairs per mm was considered essential to maintain diagnostic accuracy in a receiver operating characteristic analysis with regards to undisplaced or minimally displaced fractures of the extremities.[8] This resolution size corresponds to a pixel size of 0.16 mm and the pixel size is directly related to spatial resolution. The resolution with SFR for skeletal images is typically 8 lines per mm.

Another feature is that the images may not be comparable to actual anatomical size. This makes it difficult to template on the images for preoperative planning for surgery. For instance, the template available for planning hip replacement surgery are generally 15% to 20% magnified, which fits in with the SFR. It is not possible to template on a digital image with a different magnification as the conventional templates will not match the image. To overcome this limitation, some implant manufacturing companies are coming up with digital templating options.

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COMPATIBILITY OF DIGITAL IMAGING AND PACS

PACS refers to the electronic management of digital images.[9] This technology was developed at the same time as digital radiography in the mid-1980s and has come a long way since. The popularity of CR has generated an expansion of PACS services as the conventional SFR was incompatible with this system. Modern PACS require substantial infrastructure and aim to perform the entire range of functions (fig 2) including image acquisition, display of soft copies on monitors, transmission of the images on the local area network, storage of images for quick access, permit access to the radiology information service and the hospital information service, and finally, generation of hard copies.[10] More recently, with the widening presence of teleradiology, wide area networks require PACS at the transmitting and receiving ends. CAD (computer aided digitisation) and CADx schemes are available that can point out an abnormal area to the radiologist but at present, these are of limited value in musculoskeletal imaging.

The digital imaging and communications in medicine (DICOM 3.0 standard) was established through the collaboration of the American College of Radiology and National Equipment Manufacturing Association.[11] The current grey scale display monitors for soft copy reporting have resolution of 2K×2.5K×8/12 bit resolution.

The requirements for a good PACS are efficient grey scale work station display protocols, fast interfaces, and scalability. To achieve good throughput rates, it is essential that all components of the PACS work at comparable data transfer speeds so that the images can be transferred and viewed without delay.

Reversible compression of images further increases the storage capacity of the archival systems and the images can be restored to original size and quality at a later date without loss of information. Irreversible compression generally results in loss of information and should be avoided.

REVIEW OF FUTURE TRENDS IN RADIOLOGICAL IMAGING AND POTENTIAL CLINICAL IMPLICATIONS

The important advantage of digital imaging is cost and access. The hospitals save money from lower film cost, reduced requirement for storage space, and lesser staff required to run the services and archiving sections. The images are instantly available for distribution to the clinical services without the time and physical effort needed to retrieve film packets and reviewing previous imaging on a patient is much easier.

Spatial resolution was limited in earlier versions of CR but newer versions have overcome this problem. Flat panel CR is another technological advancement. The yield of electrons is five times as compared with CR and it gives a superior image quality and dose efficiency.

Solid state flat panel DR provides better quality than CR or SFR and at the same time requires a lower radiation dose. These are composed of *x* ray detector material superimposed on micro circuit array. The indirect version of this technology exhibits a much better signal to noise ratio. A portable version has also been devised. The direct DR version, amorphous selenium replaces the photo sensors. It is very useful for imaging of extremities and shows the trabecular bone pattern very well. The clinical utility of these recent developments is still under evaluation but it is probable that the overwhelming advantages offered by these newer modalities will lead to their widespread use.

Standing where we are in digital imaging, it is not hard to see that the future is digital. More and more hospitals are likely to set up PACS in the UK like many other countries. As we embrace the filmless radiology departments, it is important to uphold evidence based medicine and at the same time to provide a personalised medicine tailored to the history of an individual patient.[12] Better detectors, faster processing, more powerful computers, bigger and sharper displays, efficient archiving will once again transform the way we look at medical imaging.[13] The display of images that is on cathode ray tubes is being replaced by flat panel high resolution LCD. Projection and virtual displays may also have a role in future. The PACS will enable integration with the radiology information system and electronic patient records and will transform medical care and be a valuable help to patient's journey through the hospital.

SELF ASSESSMENT QUESTIONS (TRUE (T), FALSE (F); ANSWERS AT THE END OF THE REFERENCES)

1. Phosphor plates are used in digital radiography.
2. Computed radiography has a wider linear dynamic range in the dose response curve compared with screen film radiography.
3. Templating is easier on digital radiography because the images are comparable to anatomical size.
4. Spatial resolution is better in digital radiography by an order of magnitude compared with screen film radiography.
5. Solid state flat panel detectors provide better quality with less radiation dose compared with screen film radiography.

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ANSWERS

1. T; 2. T; 3. F; 4. F; 5. T.